DUST EVOLUTION MODELING IN THE DISK-BUILDING STAGE

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Wada et al. 2018

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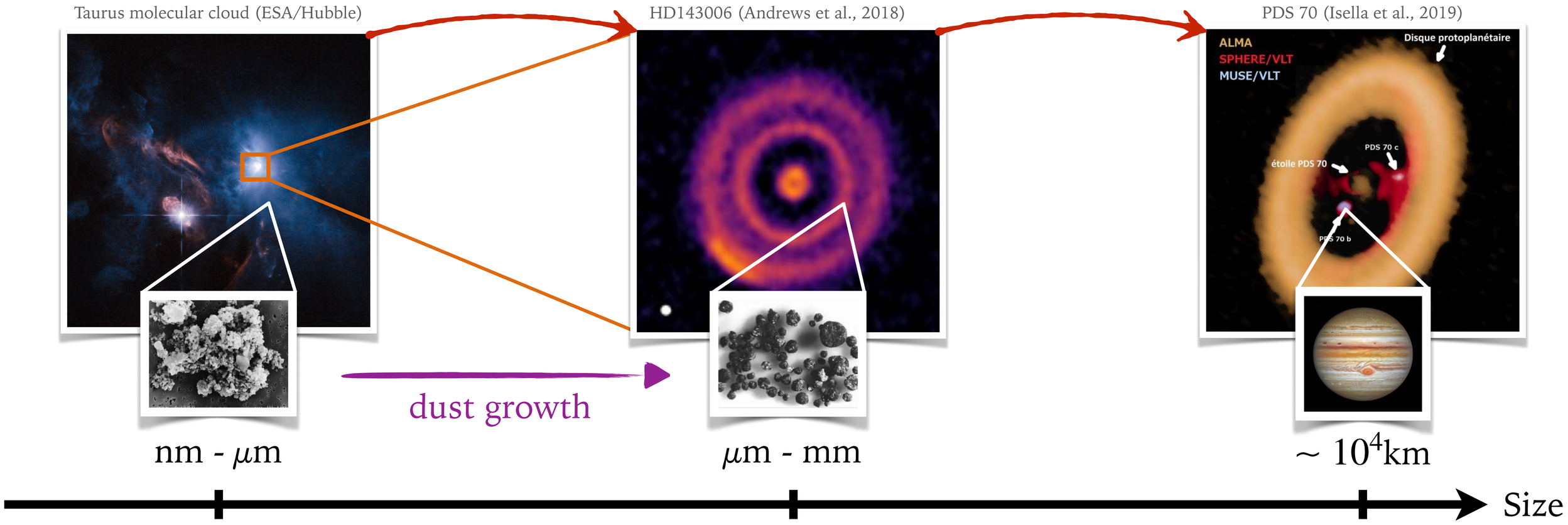
ASNUM, 2025/12/17, Grenoble

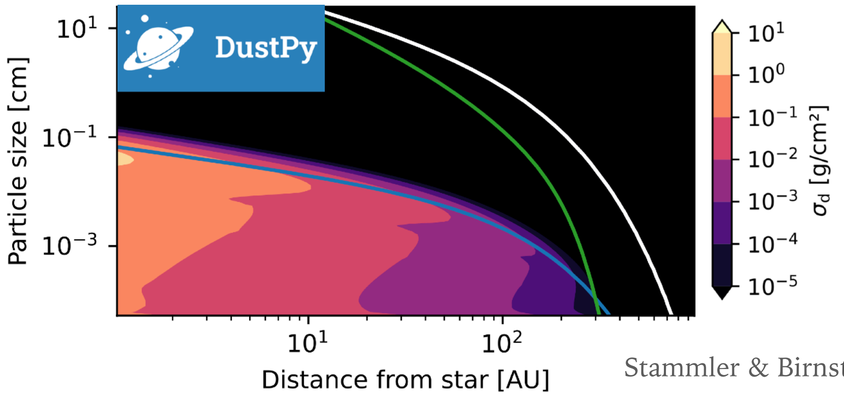
The first seeds for planets may form in less than a few million years.
How early do pebbles form around YSOs ?



Dust growth must be an efficient process !

3D SIMULATIONS WITH DUST COAGULATION/FRAGMENTATION

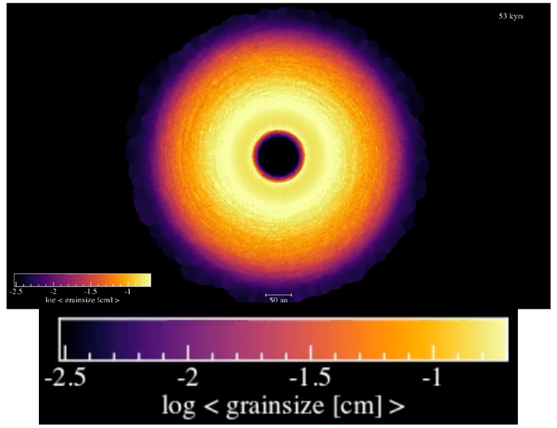
discs



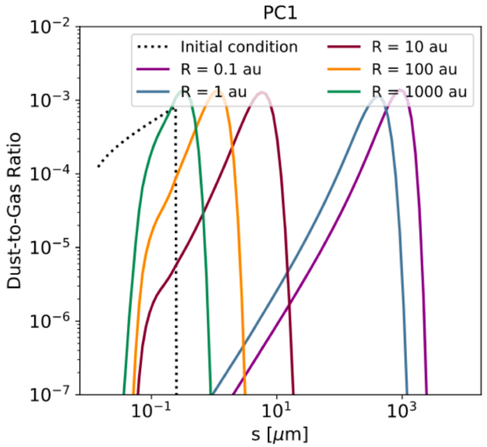
Stammler & Birnstiel, 2022

PHANTOM

Vericel et al., 2021



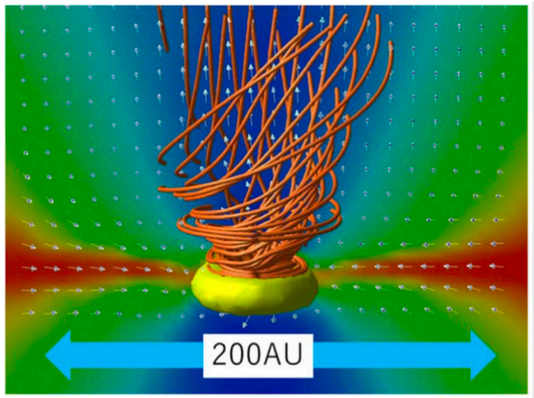
protostellar collapses



Lebreuilly et al., 2023

SHARK

Tsukamoto et al., 2021



gas and dust dynamic in 1D

single dust size approximation

dust size distribution

gas and dust dynamic in 3D

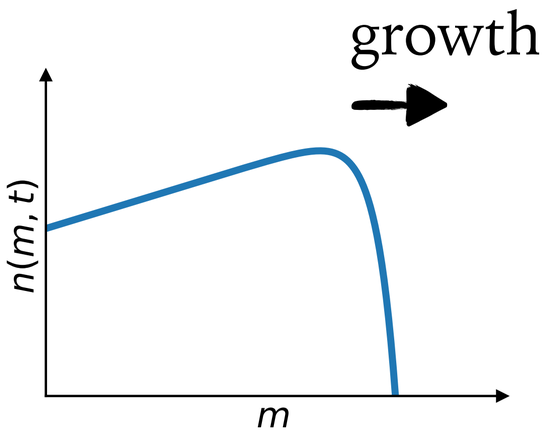
3D SIMULATIONS WITH DUST COAGULATION

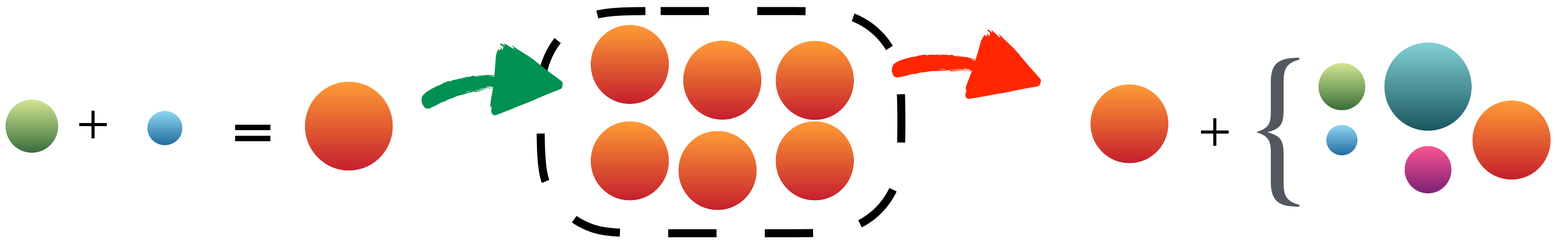
Marian Smoluchowski (1872-1917)

Model:

- mean-field theory (fluctuation of physical quantities are neglected)
- binary collision
- spherical particles
- collision with coalescence

3D SIMULATIONS WITH DUST COAGULATION





$$\frac{\partial n(m,t)}{\partial t} = \underbrace{\frac{1}{2}\int_0^m K(m', m-m')n(m',t)n(m-m',t)dm'}_{\text{gain}} - \underbrace{n(m,t)\int_0^\infty K(m,m')n(m',t)dm'}_{\text{loss}}$$

m, m': masses

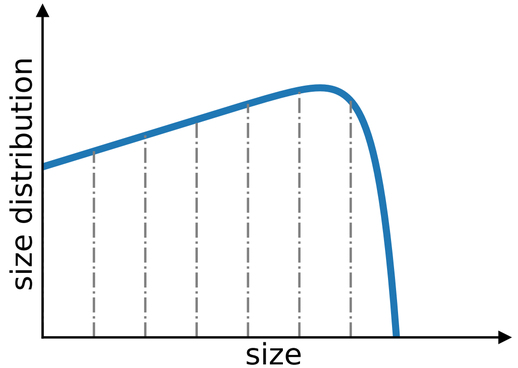
n : number density of particles per mass unit

K: collision kernel

$K(m_1, m_2) = \sigma(m_1, m_2)\Delta v(m_1, m_2) \rightarrow$ need numerical solutions

Requirements

- 3 orders of magnitude in size (1μm - 1mm) $\Leftrightarrow$ 9 orders in mass
- mass range discretization $\rightarrow$ 20 mass bins (low numerical cost)



Discontinuous Galerkin scheme

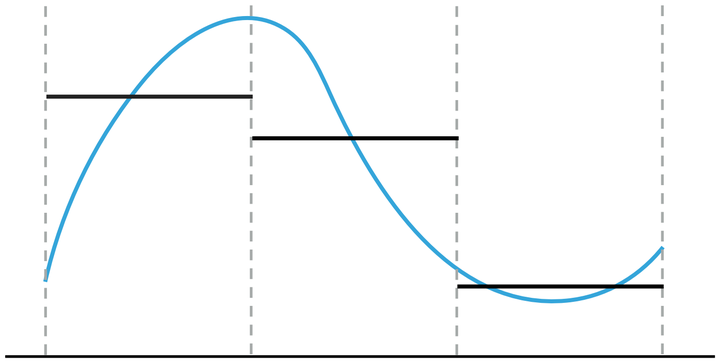
conservative form (Tanaka et al., 1996)

COAgulation with Lightning fast Algorithm

Liu et al., 2019
Lombart & Laibe, 2021

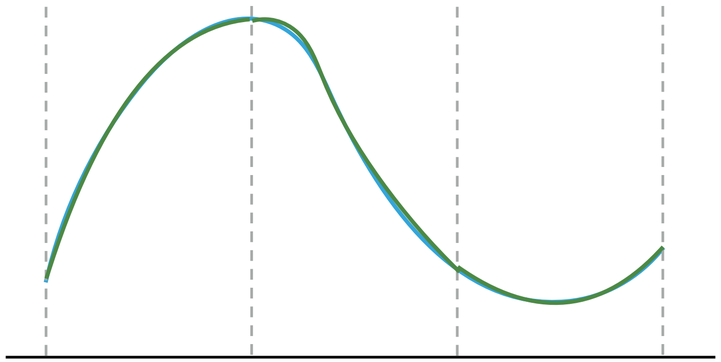
$$\begin{cases} \dfrac{\partial g(m,t)}{\partial t} + \dfrac{\partial F_{\text{coag}}[g](m,t)}{\partial m} = 0 \\ F_{\text{coag}}[g](m,t) = \displaystyle\int_0^m \int_{m-m_1}^{\infty} \frac{K(m_1,m_2)}{m_2} g(m_1,t) g(m_2,t) \mathrm{d}m_2 \mathrm{d}m_1 \end{cases}$$

constant



Before

polynomials



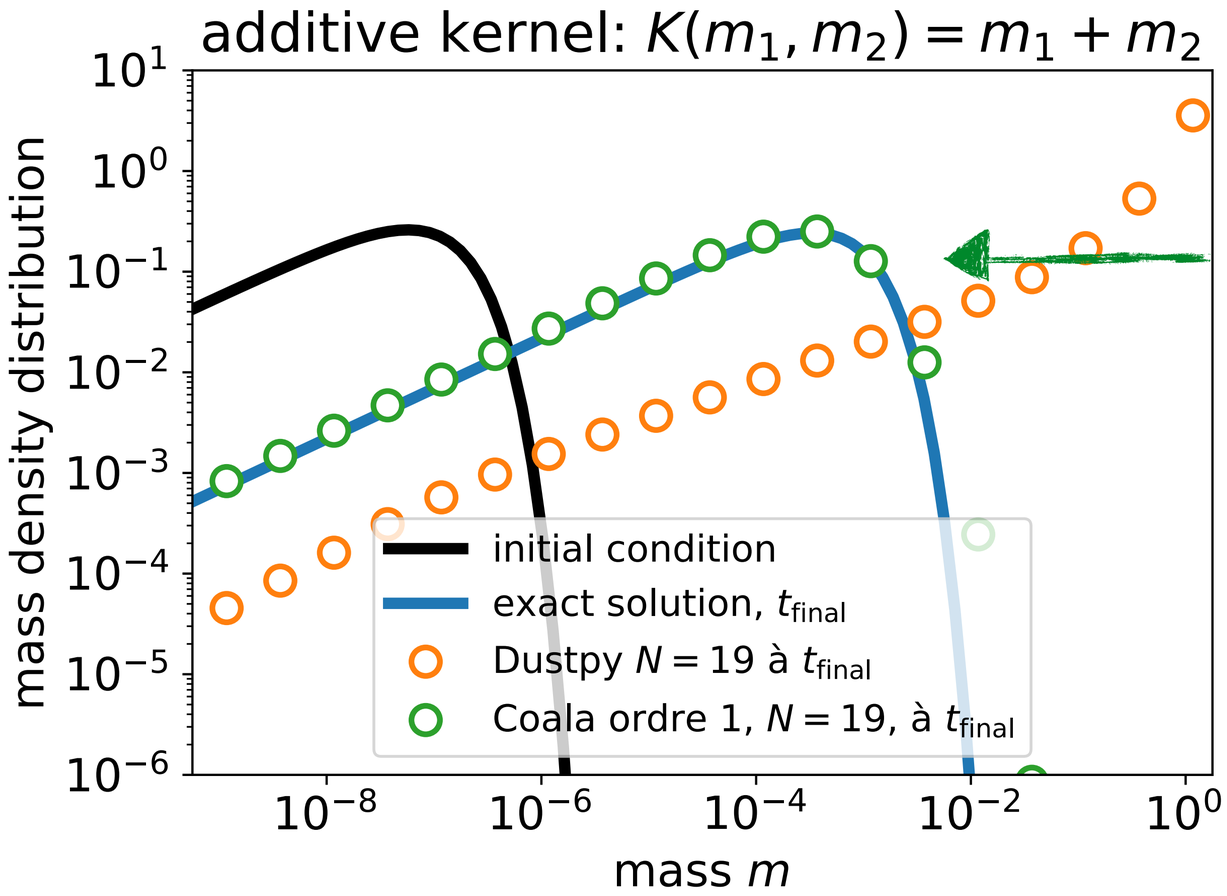
Now

→high accuracy

→few number of mass bins

BENCHMARK COALA

Lombart & Laibe (2021), Laibe & Lombart (2022)



(linear piecewise approximation)

COALA

vs

DustPy

Requirements

- ✔ 9 orders of magnitude in mass
- ✔ 10-20 dust size bins

3D simulations with polydisperse coagulation

DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025 (minor revisions)

RAMSES MHD model of B335-like protostar
gas & dust (40 bins)

Implementation:

- dust growth as source term of continuity equation

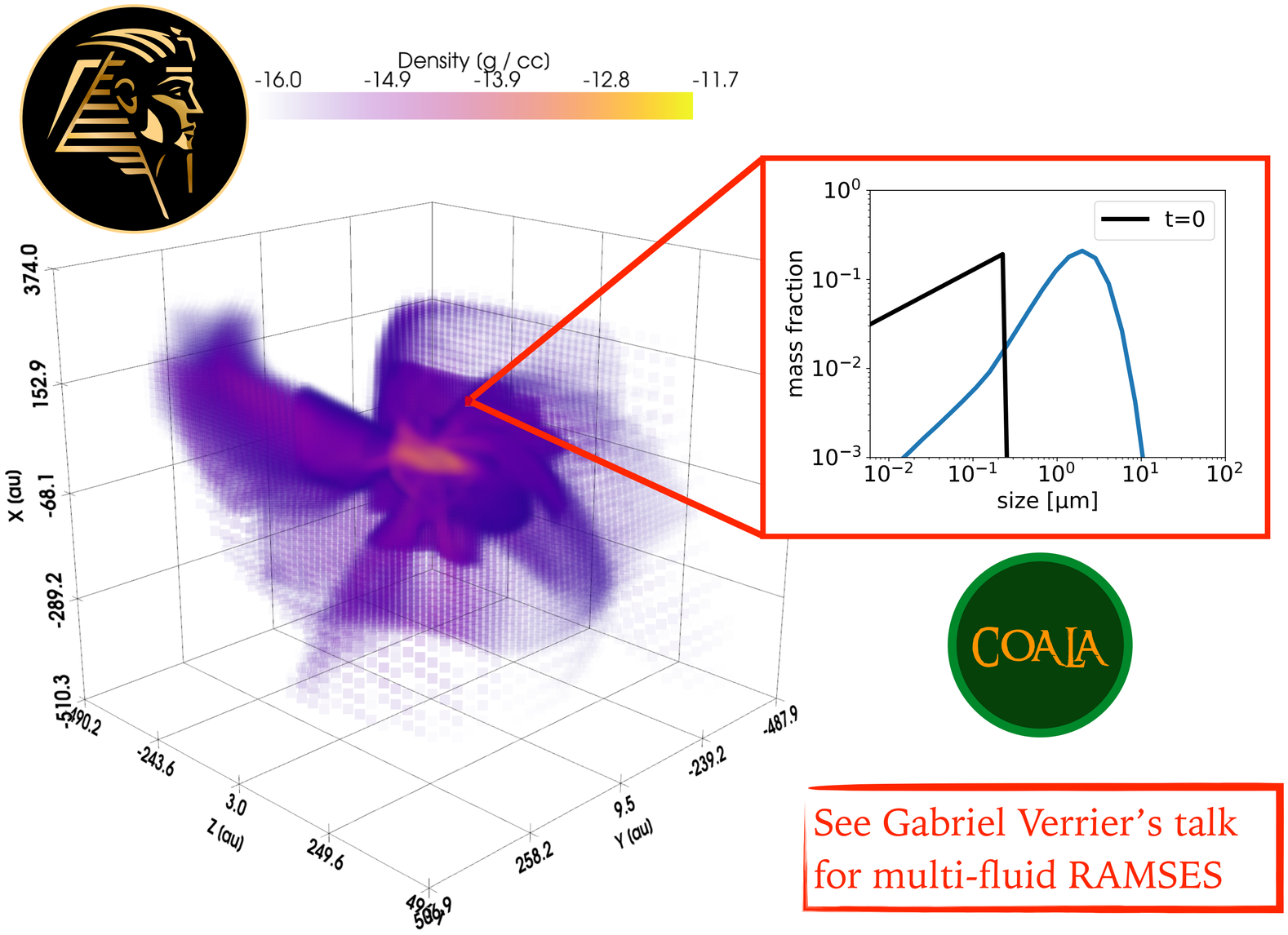
$$\frac{\partial \rho_k}{\partial t} + \nabla \cdot [\rho_k \mathbf{v}_k] = \left.\frac{\partial \rho_k}{\partial t}\right|_{\text{growth}}$$

$$\rho_k = \int_{I_k} g(m,t)\mathrm{d}m$$

- ordinary operator splitting

$$\rho_k^* = \rho_k(t_n) - \Delta t \left(\nabla \cdot [\rho_k \mathbf{v}_k] \right) \rightarrow \text{RAMSES}$$

$$\rho_k(t_{n+1}) = \rho_k^* + \Delta t \left.\frac{\partial \rho_k}{\partial t}\right|_{\text{growth}} \rightarrow \text{COALA}$$



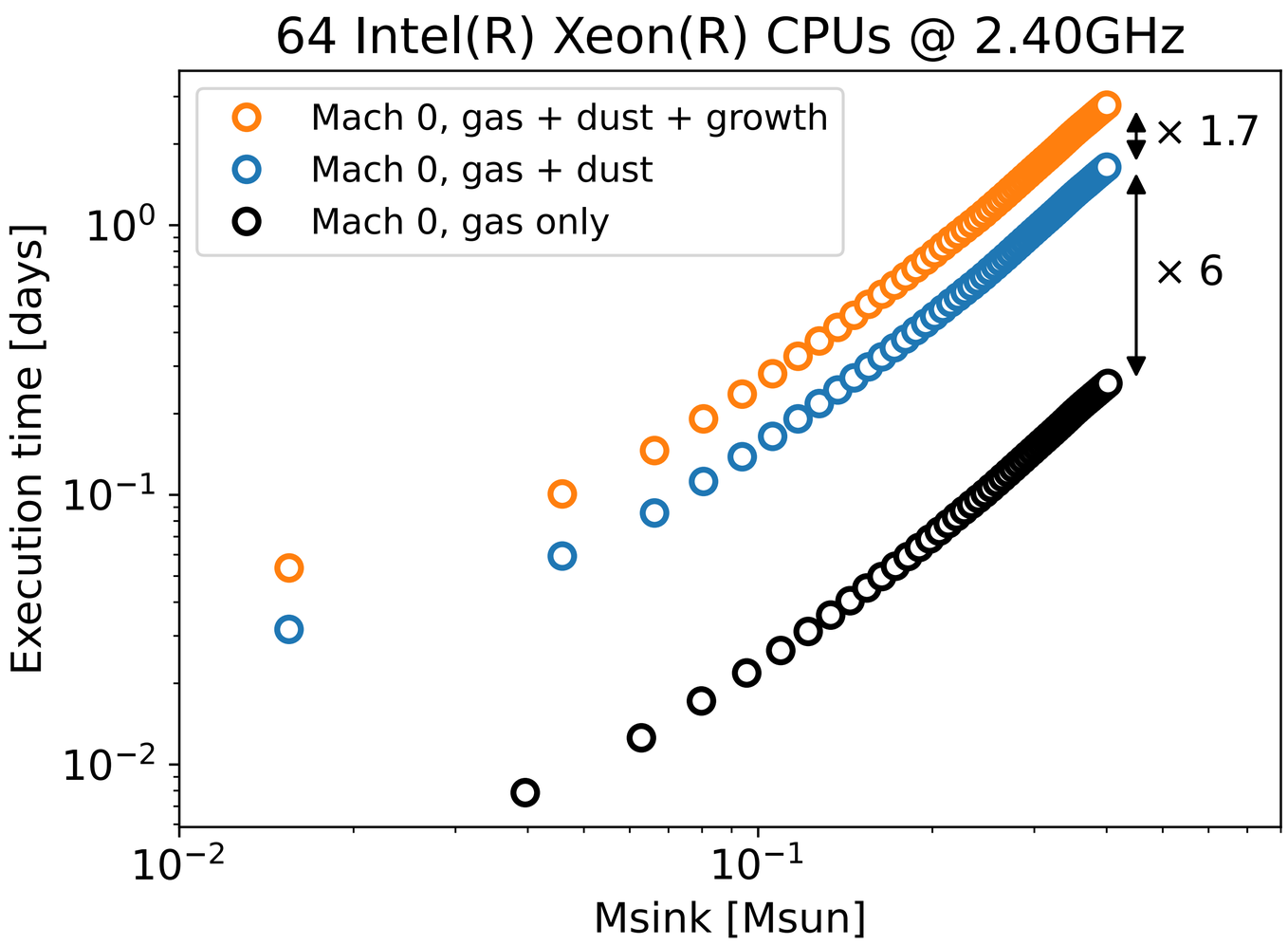
COALA

See Gabriel Verrier's talk for multi-fluid RAMSES

DUST GROWTH IN PROTOSTELLAR COLLAPSE

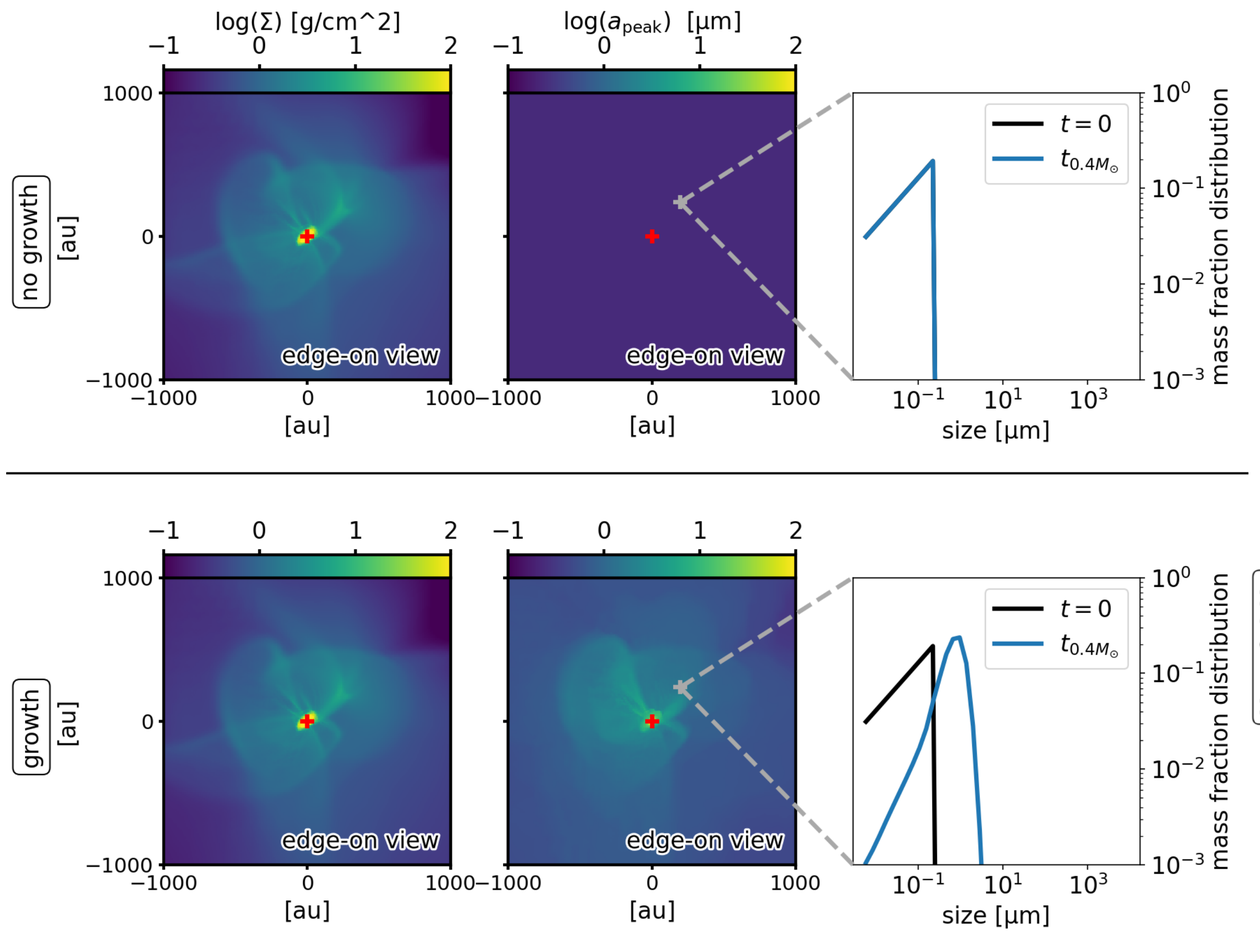
Lombart et al., 2025 (minor revisions)

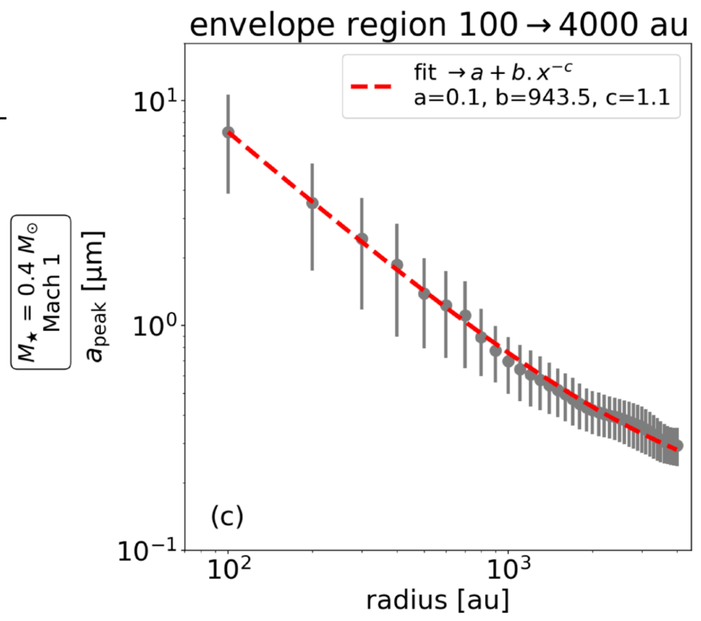
dust size range discretized with **40 bins**



DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025 (minor revisions)





Mass of grains in the envelope
(in % of total dust mass)

Initially (MRN distribution):

- ~ 0,25 μm → 20%
- ~ 5 μm → 0%

After 100 kyrs:

- ~ 0,25 μm → 13%
- ~ 5μm → 1%

DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025 (minor revisions)

Initial dust-to-gas ratio $\theta_0 = 0.01$

$$\epsilon = \frac{\rho_{\rm d}}{\rho_g + \rho_{\rm d}} \text{ and } \epsilon_0 = \frac{\theta_0}{1+\theta_0}$$

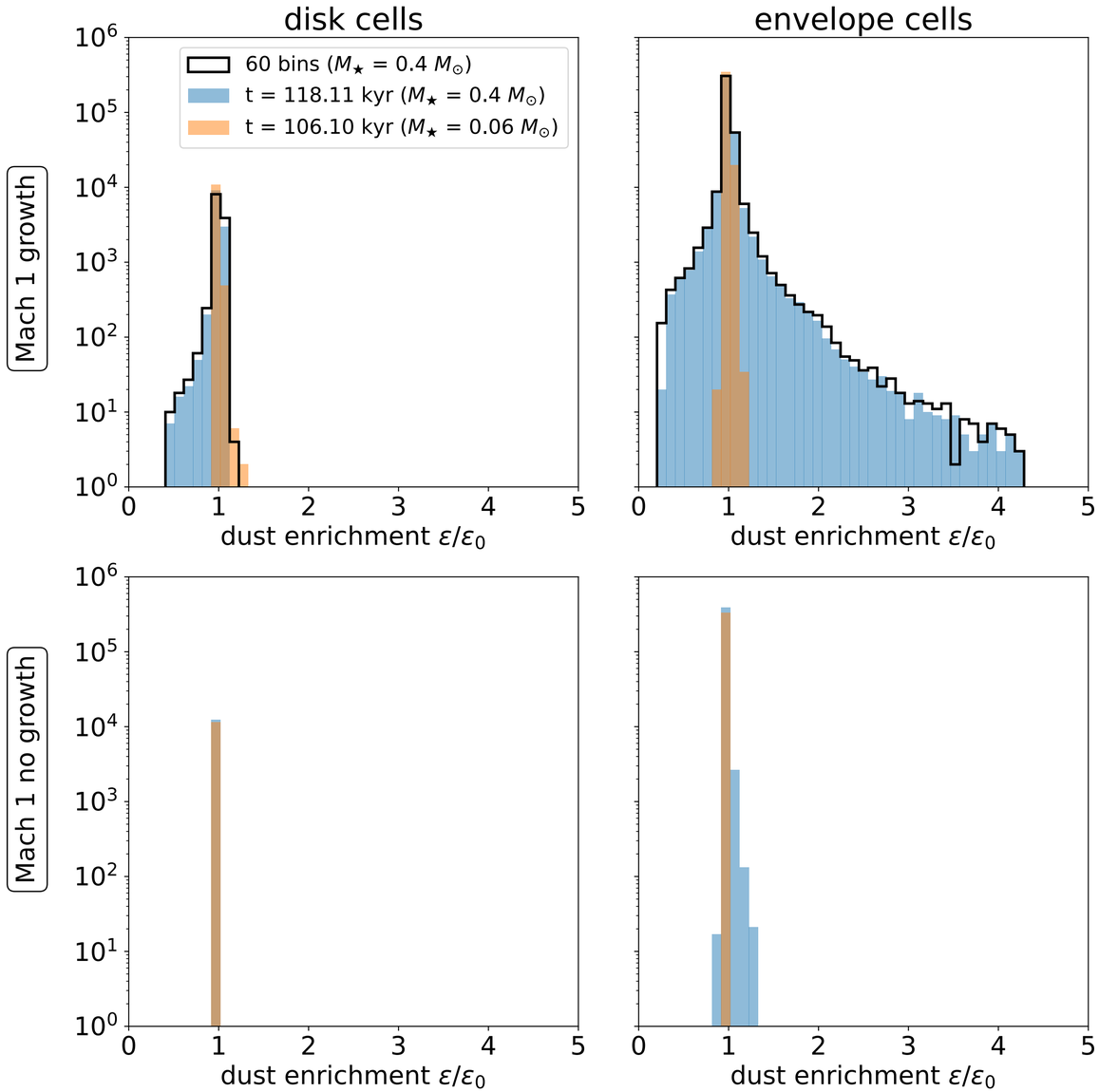
Main mechanism for differential grain-grain velocity is from turbulence Ormel's model:

$$\Delta v_{i,j} \propto \sqrt{\alpha} c_s \sqrt{S_t}$$

$\alpha \rightarrow$ level of turbulence

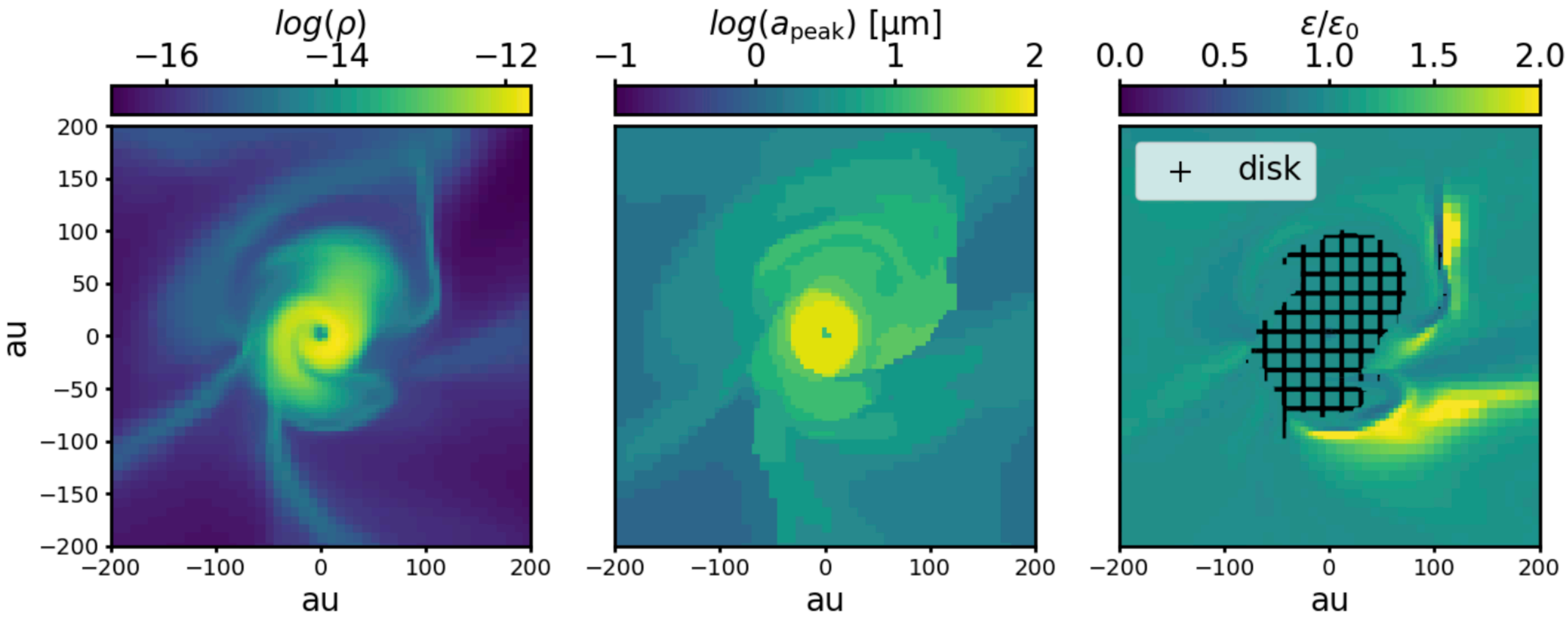
In envelope: $\alpha = 1.5$

In Disk ($n_g > 10^9 \mathrm{cm}^{-3}$): $\alpha = 10^{-4}$



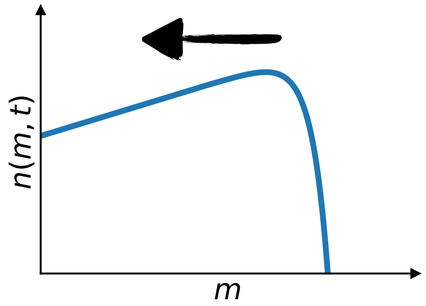
DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025 (minor revisions)



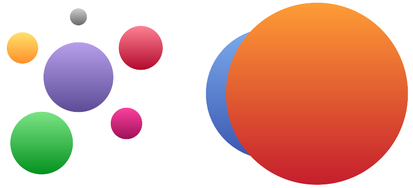
DUST FRAGMENTATION MODEL

fragmentation

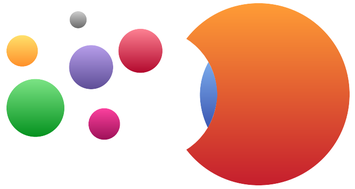


Destructive fragmentation

Mass transfer



Mass transfer + cratering



$$\frac{\partial n(m,t)}{\partial t} = \frac{1}{2}\int_0^\infty\int_0^\infty K(m_1,m_2)\underbrace{b(m,m_1,m_2)}_{\text{mass distribution of fragments}}n(m_1,t)n(m_2,t)\mathrm{d}m_1\mathrm{d}m_2 - n(m,t)\int_0^\infty K(m,m_1)n(m_1,t)\mathrm{d}m_1$$

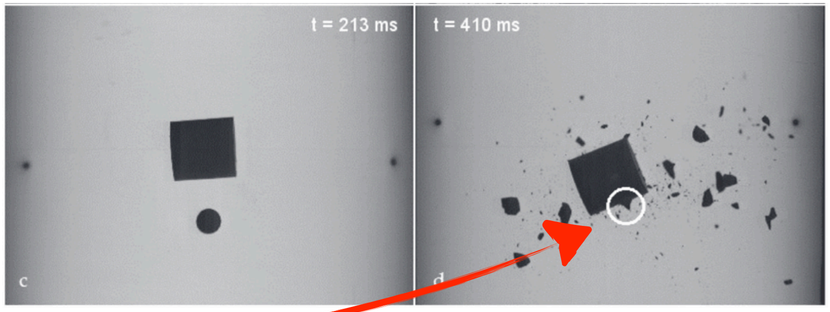
Safronov, 1972; Jones et al., 1996; Suttner et al., 2001; Blum, 2006; Hirashita et al., 2009; Rafikov et al., 2020

Conservative form (Lombart et al. 2024):

$$F_{\mathrm{frag}}[g](m,t) = \frac{1}{2}\int_0^m\int_0^\infty\int_0^\infty \mathbf{1}_{m_1+m_2\geq m}\frac{m_\mathrm{f}}{m_1m_2}b(m_\mathrm{f},m_1,m_2)K(m_1,m_2)g(m_1,t)g(m_2,t)\mathrm{d}m_2\mathrm{d}m_1\mathrm{d}m_\mathrm{f}$$

$$-\int_0^m\int_{m-m_1}^\infty \frac{K(m_1,m_2)}{m_2}g(m_1,t)g(m_2,t)\mathrm{d}m_2\mathrm{d}m_1$$

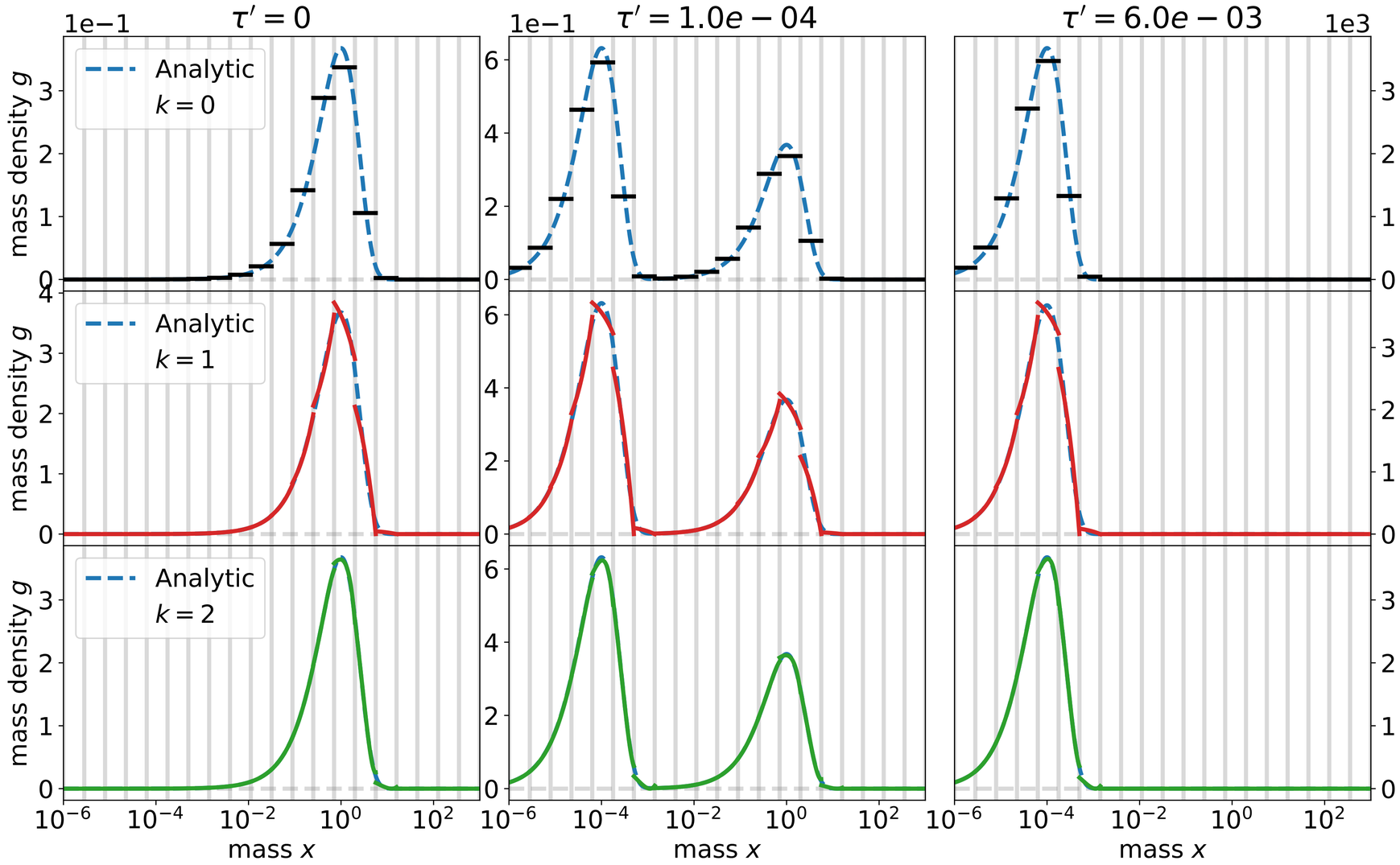
Bukhari Syed et al. 2017



DUST FRAGMENTATION MODEL

Benchmark for fragmentation

Lombart et al. 2024



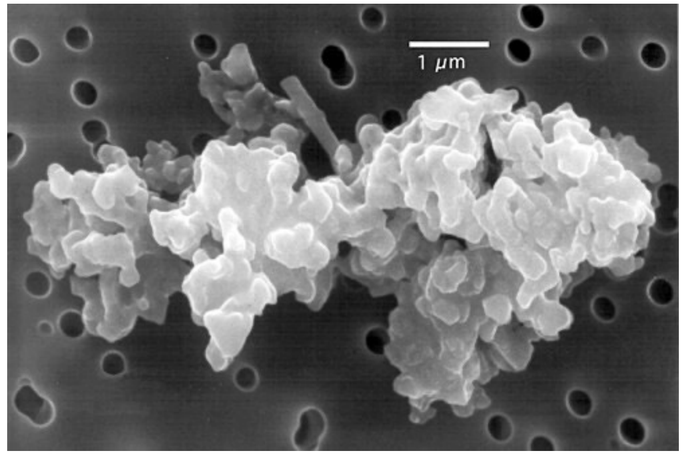
Feingold et al., 1988

$K(u, v) = 1$

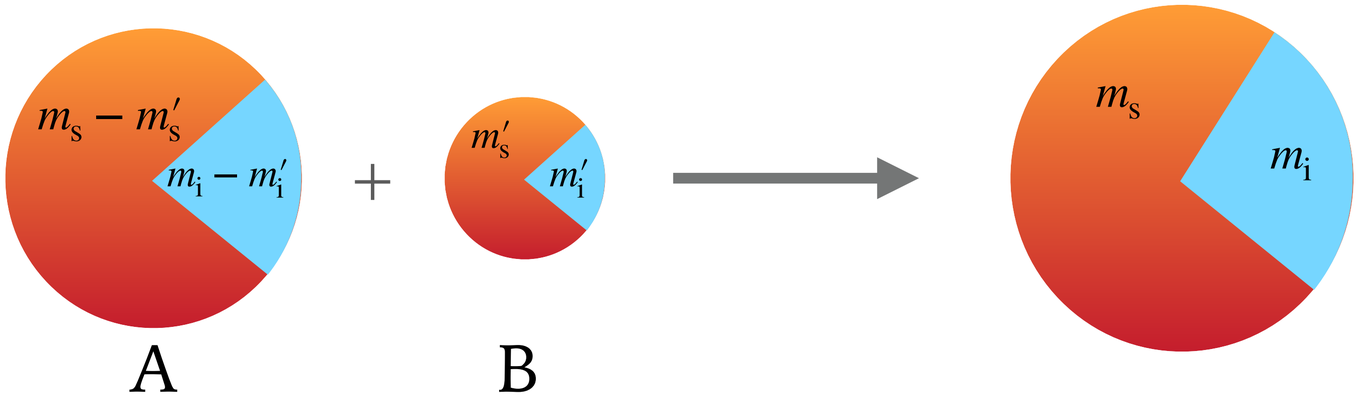
$b(w, u, v) = \gamma^2(u + v)e^{-\gamma w}$

3D simulations with polydisperse general non-linear fragmentation

Growth and fragmentation of multi-component dust aggregates



MULTI-COMPONENT DUST COAGULATION



Need 2D Smoluchowski coagulation equation

$$\frac{\partial n(m_s, m_i, t)}{\partial t} = \frac{1}{2}\int_0^{m_s}\int_0^{m_i} K(m_s - m_s', m_s', m_i - m_i', m_i')n(m_s', m_i', t)n(m_s - m_s', m_i - m_i', t)\mathrm{d}m_s'\mathrm{d}m_i' - \int_0^{\infty}\int_0^{\infty} K(m_s, m_s', m_i, m_i')n(m_s, m_i, t)n(m_s', m_i', t)\mathrm{d}m_s'\mathrm{d}m_i'$$

$$K(m_s - m_s', m_s', m_i - m_i', m_i') = P_{\mathrm{stick}}(m_s, m_s', m_i, m_i', \Delta v)\sigma\Delta v$$

Sticking probability

$$P_{\mathrm{stick}}(m_s, m_s', m_i, m_i') = \epsilon_{\mathrm{s-s}}\frac{m_{\mathrm{s,A}}}{m_{\mathrm{A}}}\frac{m_{\mathrm{s,B}}}{m_{\mathrm{B}}} + \epsilon_{\mathrm{s-i}}\left(\frac{m_{\mathrm{s,A}}}{m_{\mathrm{A}}}\frac{m_{\mathrm{i,A}}}{m_{\mathrm{A}}} + \frac{m_{\mathrm{s,B}}}{m_{\mathrm{B}}}\frac{m_{\mathrm{i,B}}}{m_{\mathrm{B}}}\right) + \epsilon_{\mathrm{i-i}}\frac{m_{\mathrm{i,A}}}{m_{\mathrm{A}}}\frac{m_{\mathrm{i,B}}}{m_{\mathrm{B}}}$$

Sticking efficiency of s-s collision

Sticking efficiency of s-i collision

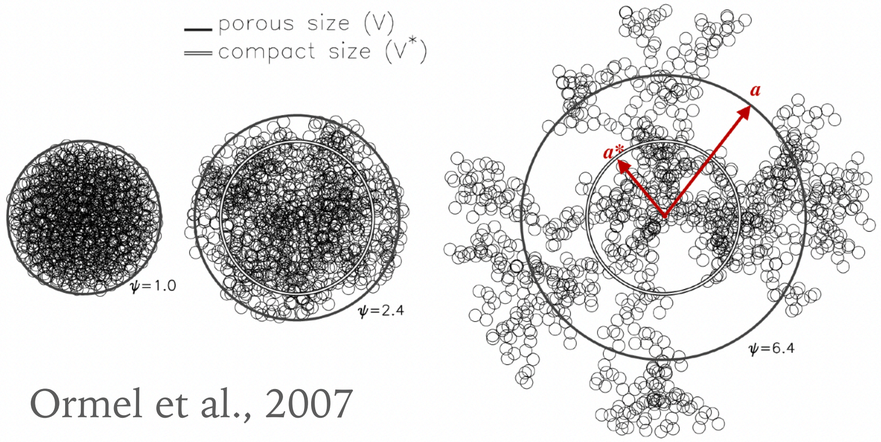
Sticking efficiency of i-i collision

Need data from lab experiments

Laurenzi+2002; Vale+2005; Alexopoulos+2009

DUST AGGREGATION

Dust aggregate is defined by its mass m and porosity $\psi = \dfrac{V}{V*}$



Ormel et al., 2007

Need 2D Smoluchowski coagulation equation

$$\frac{\partial n(m,\psi_m,\tau)}{\partial t} = \frac{1}{2}\int_0^m \int_{\psi_{\min}}^{\psi_{\max}} \int_{\psi_{\min}}^{\psi_{\max}} K(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1})n(m_1,\psi_{m_1},t)n(m-m_1,\psi_{m-m_1},t)\delta(\psi_m-\Gamma(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1}))\mathrm{d}\psi_{m-m_1}\mathrm{d}\psi_{m_1}\mathrm{d}m_1$$

$$-n(m,\psi_m,t)\int_0^\infty \int_{\psi_{\min}}^{\psi_{\max}} K(m,\psi_m;m_1,\psi_{m_1})n(m_1,\psi_{m_1},t)\mathrm{d}\psi_{m_1}\mathrm{d}m_1$$

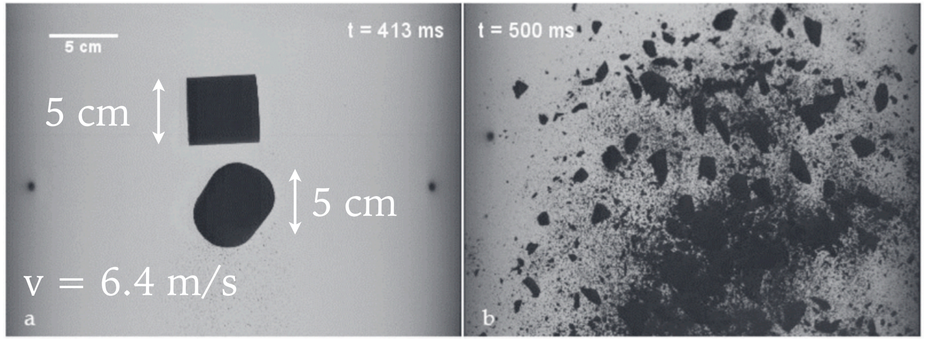
$\Gamma(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1}) \rightarrow$ determine the porosity of the resulting aggregate

Blum, 2006; Ormel et al., 2007; Okuzumi et al., 2009; Hirashita et al., 2021

FRAGMENTATION OF MULTI-COMPONENT DUST AGGREGATES

Multi-component dust:

→ how to model the composition of fragments ?



Dust aggregates:

→ how to model the mass and porosity of the fragments ?

Need data from lab experiments

Blum, 2006; Ormel et al., 2007; Okuzumi et al., 2009; Hirashita et al., 2021; Hasegawa et al., 2022

CHARACTERIZING DUST EVOLUTION DURING THE DISK-BUILDING STAGE

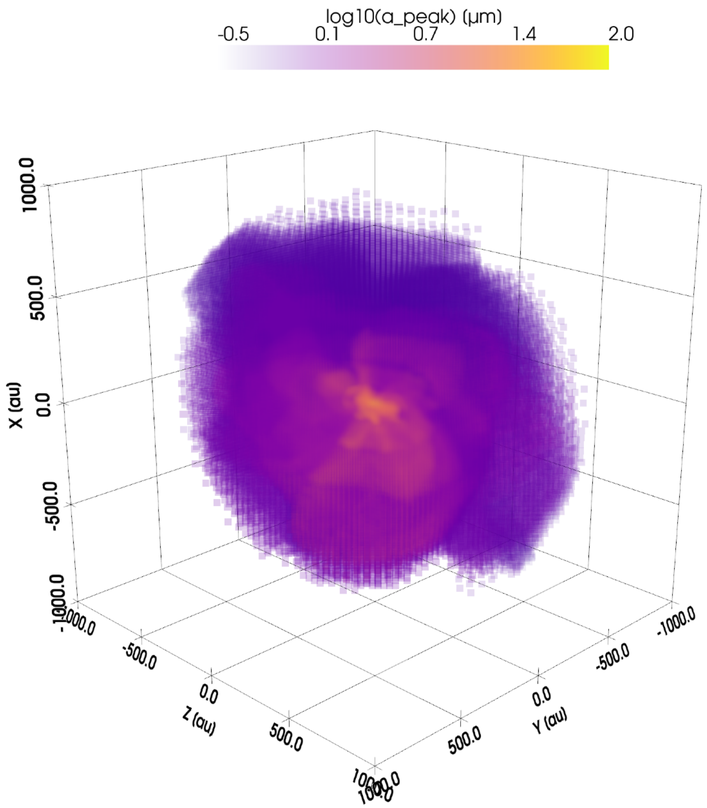
+

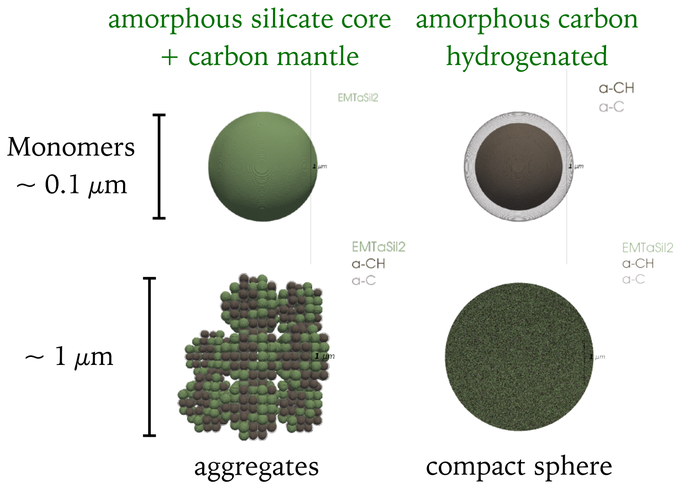
Carpine et al., 2025

Realistic dust optical properties

THEMIS

The Heterogeneous dust Evolution Model for Interstellar Solids





Radiative transfer codes

Realistic synthetic observations

TAKE HOME MESSAGES

- The **size evolution** of dust particles are modeled by **Smoluchowski-like equations**.
- **3D simulations with polydisperse dust coagulation/fragmentation**
  - 9 orders of magnitude in mass (1μm - 1mm)
  - Few number of bins $\sim$ 20
  - Good accuracy

- **Dust grains are predicted to grow by <u>2 orders of magnitude</u> in collapsing envelopes (just gravity/turbulence, without magnetic effects yet)**

- Coagulation/fragmentation of **dust aggregates** and **multicomponent dust** can be modeled by **2D extension**.
- **PEBBLES**: realistic synthetic observations by combining simulations, radiative transfer with realistic dust optical properties